Acceleration for HEMCs

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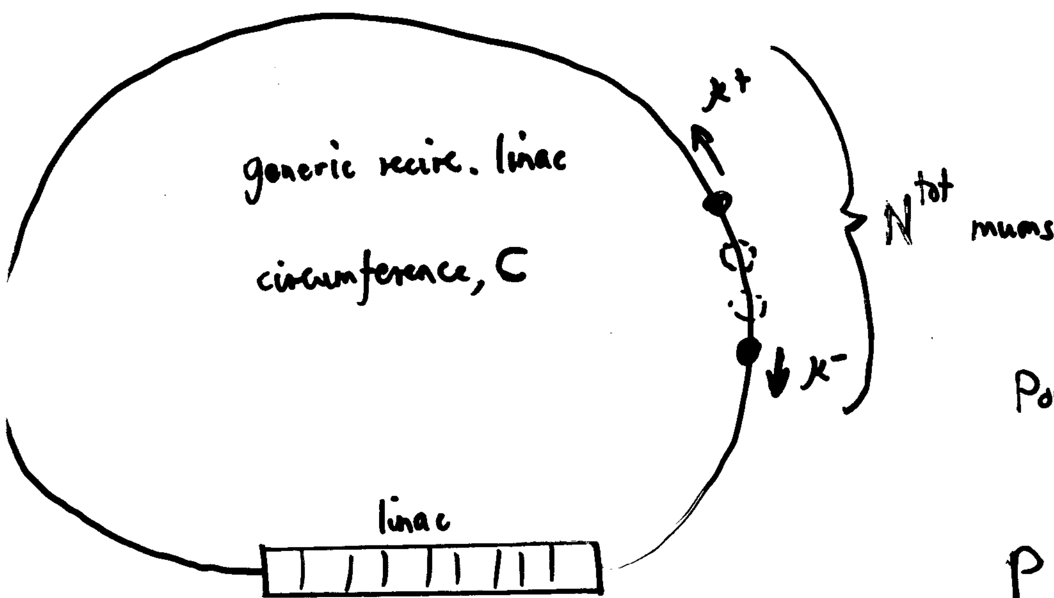
Topics:

- acceleration strategy for HEMC's
- mu - TESLA

Q. Why can \$/GeV of Acceleration be much less for HEMC's than $\left\{ \begin{matrix} \nu \text{ Facts} \\ \text{Higgs factory} \end{matrix} \right.$?

A. because power to the rf cavities of the recirc. linac can be matched to the beam
$\Rightarrow$ allows high efficiency power to beam & higher f cavities (cheaper)



g = ave. accel. gradient

f = frequency

Energy extracted/meter/pass, $U[J/m] = 38 \times N^{tot}[10^{13}] \times \dfrac{g}{24\,\text{MeV/m}}$

c.f. $U^{stored}[J/m] \approx \underset{\text{TESLA}}{50} \times \left(\dfrac{1.3\,\text{GHz}}{f}\right)^2 \times \left(\dfrac{g}{24\,\text{MeV/m}}\right)^2$

Power extracted/m, $P = U\left(\dfrac{\overset{3\times10^5\,\text{km/s}}{c}}{C}\right)$

$$P\,[kW/m] \approx 11500 \times \underbrace{\frac{N^{tot}[10^{13}]}{C[km]} \times \frac{g}{24\,\text{MeV/m}}}_{\text{need } \lesssim 0.05-0.1}$$

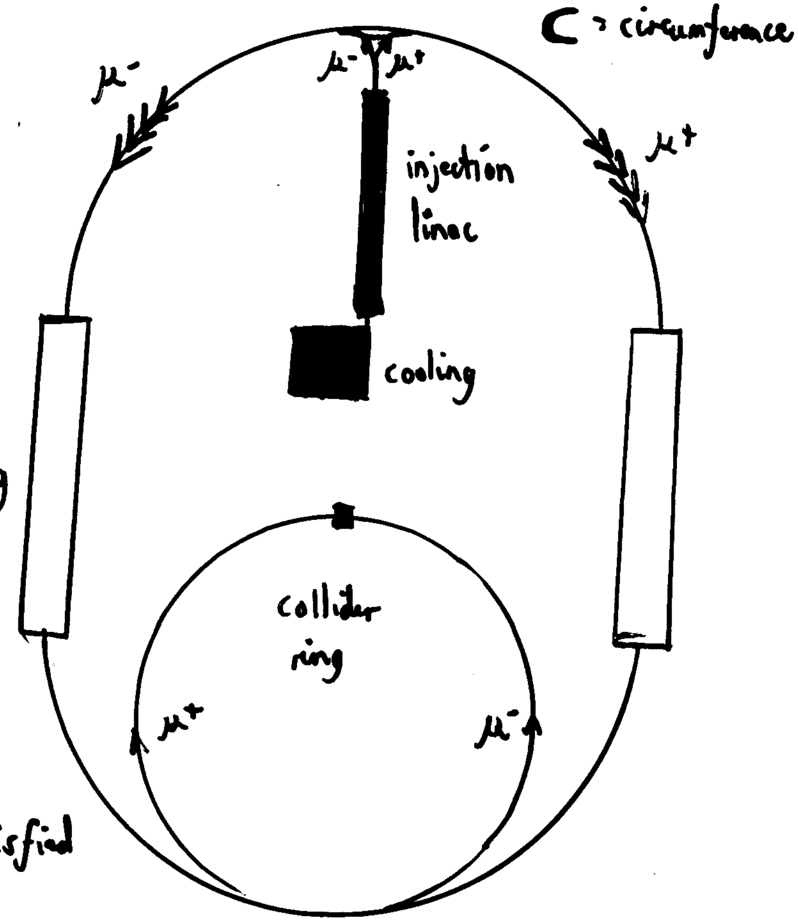
c.f. KEK-B $P \approx 380$ kW/m
ν Fact $P \approx 500$ kW/m

$\Rightarrow$ large C, small N
only works for HEMC's

A Sensible Acceleration Strategy for (Stand-alone) HEMC's

Work downwards from collision energy:

1) choose parameters (C, E_{rf}, f, g) for final recirc. linac
   - use FFAG or fast-ramping synchrotron
   - match rf power to beam
   - require $\frac{E_{rf}}{C} \gg \frac{m_\mu}{c\tau_\mu} = 0.16$ MeV/m (decays)



2) use the same ring & same rf for all recirculating passes at lower energies, down to the lowest energy appropriate for that rf frequency, f.

   ∴ cheap low-field magnets, no extra rf, beam power matching & decay conditions are automatically satisfied

3) find the cheapest feasible way to accelerate from the cooling channel to that injection energy (linac? linac + recirc. linac)

(Note that this optimal "stand-alone" acceleration looks very different to the upgrade scenarios from a ν factory or Higgs collider)

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An Energy Upgrade from TESLA to a High-Energy $\mu^+\mu^-$ Collider

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ABSTRACT

We discuss the possible extension of a TESLA 250×250 GeV SRF e^+-e^- linear collider to a multi-TeV μ^+-μ^- collider, by future addition of a muon source, return arcs for recirculation and a collider ring. The TESLA SRF systems are potentially also suitable for multiturn acceleration of muon bunches, and could be adapted for use in a recirculating μ-linac. Many problems and design issues would need to be resolved, and further study is needed.

I. INTRODUCTION

The TESLA collaboration is developing a proposal for a 250×250 GeV e^+-e^- linear collider based on superconducting rf (SRF) acceleration.[1] In this concept two 250 GeV linacs, for electrons and positrons, respectively, are directed collinearly into an interaction point for high-energy (500 GeV) single-pass collisions. In this note we comment that these same linacs could also be used for accelerating muons, and multiple recirculations of muons through the linacs could permit acceleration to many TeV in energy. The muons could then be transferred into a storage ring for multiturn ultrahigh energy collisions (up to ~10 TeV or more). If a suitable muon source is developed, the scenario would give TESLA a unique opportunity for a future energy upgrade by an order of magnitude or more. This arrangement would take great advantage of a previous investment in TESLA, which would provide the tunnel and SRF, (probably) the most expensive components of the upgraded facility. The phased approach of first e^+e^-, then μ^+-μ^-, allows physics to be carried out in a facility with more realizable technology in the short term, yet have the long-term potential for much higher-energy μ^+-μ^- collisions, if the difficult μ-source and design issues can be solved.

II. GENERAL DESCRIPTION

As presently envisioned the TESLA facility would have two 250 GeV linacs pointed toward each other, each ~ 15 km long and with ~10 km of active accelerating cavities. Each of these linacs would consist of relatively large aperture (7cm diameter) 1300 MHz cavities, and be capable of handling large beam power. The overall capabilities of the rf system are quite similar to the capabilities needed for the accelerator of a $\mu^+\mu^-$ Collider system. Therefore, these same linacs could also be used to accelerate muons, with the important difference that the muons could be returned in a circular transport to the linac(s) for several passes of acceleration.

Figures 1A and 1B outline conceptual configurations for the $\mu^+\mu^-$ collider upgrade. In both Figures 1A and 1B we show a collider storage ring in the center of the facility, where it could use the same detector used for the e^+-e^- linear collider. (In an optimal configuration, the collider might be at the end of the facility, with a separate detector, as in figure 2.) Muons from a muon source would be injected into a TESLA linac and accelerated to the end of the facility to an energy-matched return arc returns them for another pass through both linacs, where at the other end another energy-matched transport returns the muons through both linacs. The muons gain ~250 GeV in each passage of a linac, or 500 GeV when passing through both linacs. The process can continue through multiple passes of both linacs, with separate return transports for each pass.

This arrangement is extremely flexible in that it permits gradual energy upgrades. For example, a single pass through both linacs into a storage ring would convert the e^+e^- collider into a $\mu^+\mu^-$ collider at twice the energy. Further energy upgrades could be accomplished by additions of more passes obtained by adding more return arcs with a full-energy collider ring. The actual number of passes would be determined by physics requirements. The cost of the return arcs would be a fraction of the cost of the accelerating structures, rf power and support infrastructure. Energy upgrades by large factors are possible. For instance, 10 passes would obtain 5 TeV muons (10 TeV collisions).

In Figure 1A the muons are turned completely around in a circular path and injected backwards through the same linacs on each end. 10 linac passes would require only 5 return paths at each end. In figure 1B the beams are bent 180° and transported back to the beginning of the linacs for another 180° bend; 10 passes would require 10 complete return loops (although the long return straight path could be shared).

For a $\mu^+\mu^-$ collider both μ^+ and μ^- bunches must be accelerated. In configuration 1A the beams will be matched in energy in each return path if they start at the same point and propagate in the same direction through the linacs (circulating through the return arcs in opposite directions). In this configuration it is more natural to place the source and collider at the ends of the double linac (see figure 2).

In configuration 1B the μ^+ and μ^- bunches must propagate through the linacs in opposite directions in order to arrive at the arcs at the same energy. In this configuration it is more natural to place the source and collider at the center; the μ^+ and μ^- bunches could counterpropagate through ten passes of the linacs before being kicked into the collider ring, and be energy matched in each return arc. This configuration

Possible Configurations (Neuffer et al.)

Figure 1: Configurations for upgrading TESLA into a recirculating linac for injection into a $\mu^+\mu^-$ collider.
1A: In this configuration the μ^+ and μ^- beams are returned at the end of each linac and reinjected backwards through the same linacs, for several turns of back and forth recirculating acceleration before injection into opposing directions in a collider ring. The collider ring is in the center but could be at either end.
1B: In this configuration counter-rotating μ^+ and μ^- beams are bent 180° and transported back to the beginning of the (opposite) linacs for another 180° bend and recirculation; 10 passes would require 9 complete return loops (although the long return straight paths could be shared). We show a muon souce at the center which would launch oppositely charged bunches in opposite directions. After multipass acceleration the bunches are transferred into the collider for multiturn collisions.

Figure 1A

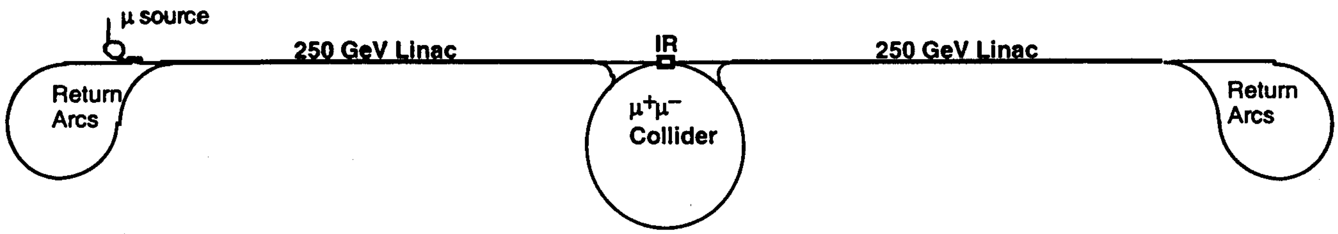


Figure 1B

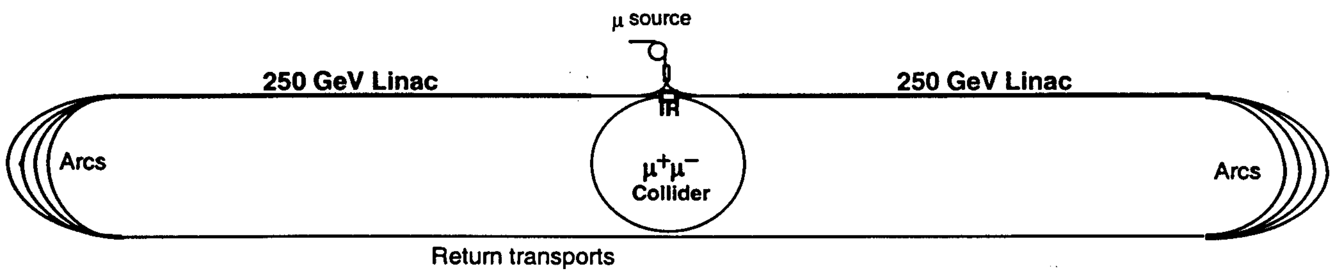
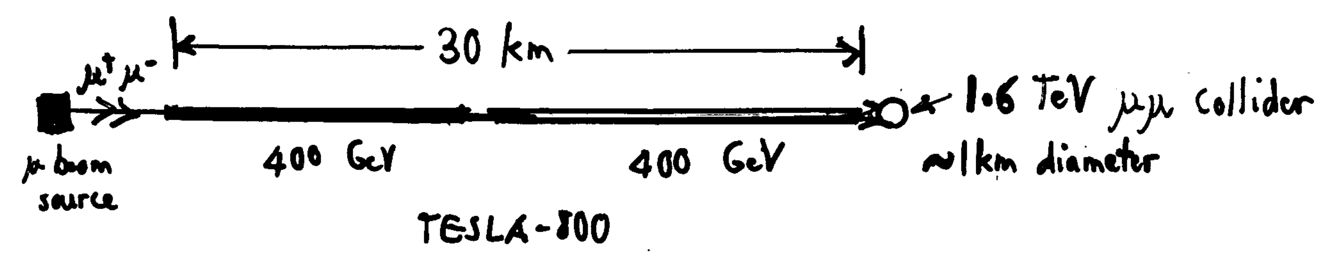
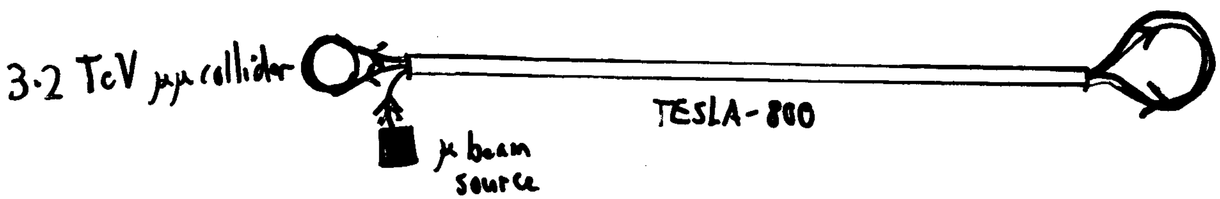


Figure 2: A variation of the figure 1A scenario. In this figure μ^+ and μ^- bunches are created at a source at the beginning of a linac, accelerated to the end of the double linac and returned back in a circular loop for a successive pass of acceleration in the opposite direction. Multipass acceleration would continue until extracted into a collider ring at the opposite (or the same) end of the linacs. (With the Collider at the opposite end an odd number of acceleration turns must occur.) 11 linac passes would require only 5 return paths at each end.

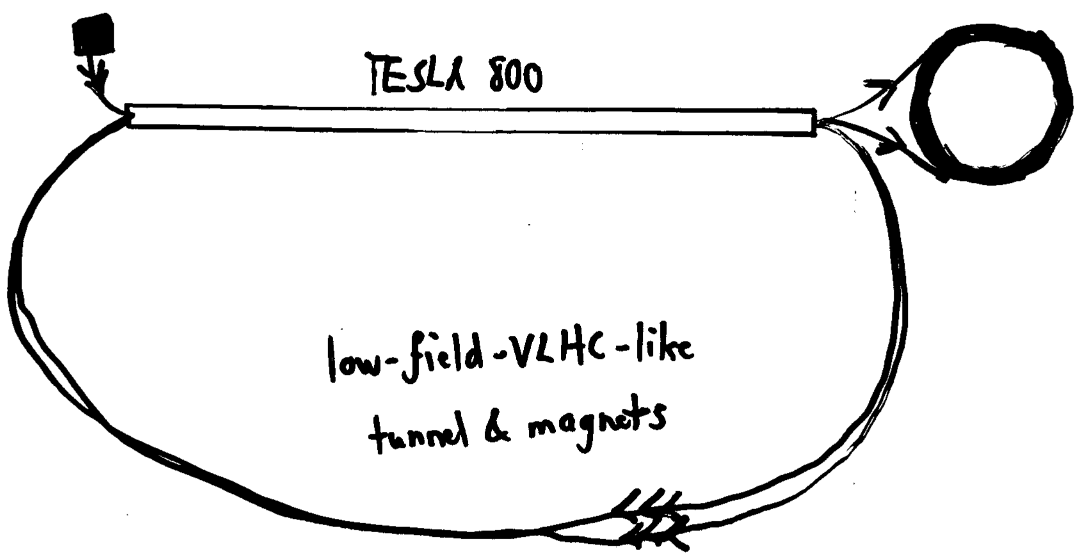
Many other configurations are possible ...



"energy doubler"



"energy quadrupler"



(N+1) x 1.6 TeV

3.2 TeV

4.8 TeV

6.4 TeV

8.0 TeV

⋮

mu-TESLA straw-man collider ring parameters

Table 1: **First pass at straw-man collider ring parameters for muon colliders using acceleration through the TESLA-800 linac – 29 April, 2001.**

collider	TESLA	mu-TESLA				
colliding projectiles	e^+e^-	$\mu^+\mu^-$	$\mu^+\mu^-$	$\mu^+\mu^-$	$\mu^+\mu^-$	$\mu^+\mu^-$
center of mass energy, E_{CoM} [TeV]	0.8	1.6	3.2	4.8	6.4	8.0
collider physics parameters:						
luminosity, $\mathcal{L}$ [$10^{34}cm^{-2}.s^{-1}$]	5.8	1.0	1.0	1.0	1.0	1.0
$\int \mathcal{L}dt$ [fb^{-1}/year]	580	100	100	100	100	100
R units: no. $\mu\mu \to ee$ evt./det/year	80 000	3400	850	380	220	140
No. of (115 GeV) SM Higgs/year	$\sim$ 400 000	85 000	100 000	120 000	130 000	130 000
CoM energy spread, σ_E/E [10^{-3}]	43	2.1	2.1	2.1	2.0	1.8
collider ring parameters:						
circumference, C [km]	–	3.0	5.0	7.0	8.4	8.7
ave. bending B field [T]	–	5.6	6.7	7.2	8.0	9.6
beam parameters:						
beam energy, E_μ [TeV]	0.4	0.8	1.6	2.4	3.6	4.0
relativistic γ factor, E_μ/m_μ	783 000	7570	15 140	22 710	30 290	37 860
(μ^- or) μ^+ bunch rep. rate, f_b [Hz]	19 544	168	24	7.0	2.3	1.0
(μ^- or) μ^+/bunch, $N_0[10^{11}]$	0.14	2.0	3.0	0.4	0.6	0.8
6-dim. norm. emit., $\epsilon_{6N}[10^{-12}m^3]$		6.0	7.0	7.7	10	12
$\epsilon_{6N}[10^{-6}m^3.(MeV/c)^3]$	1.2×10^{-9}	7.1	8.3	9.1	12	14
P.S. density, $N_0/\epsilon_{6N}[10^{22}m^{-3}]$		3.3	4.3	5.2	6.0	6.6
x,y emit. (unnorm.) [μm.mrad]		2.2	0.82	0.48	0.33	0.23
x,y normalized emit. [mm.mrad]		17	12	11	10	8.6
x,y normalized emit. [mm.MeV/c]	$(4000/8) \times 10^{-6}$	1.8	1.3	1.2	1.1	0.9
long. emittance [10^{-3}eV.s]		7.8	16	23	35	57
fract. mom. spread, δ [10^{-3}]	$0.6 \to 43$	3.0	3.0	3.0	2.8	2.5
time to beam dump, $t_D[\gamma\tau_\mu]$		0.5	0.5	0.5	0.5	0.5
effective turns/bunch		530	630	680	750	910
ave. current [mA]		7.0	1.8	0.75	1.4	0.29
synch. rad. E loss/turn [MeV]		0.05	0.5	2	5	12
synch. rad. power [kW]		0.4	0.9	1	2	3
beam power [MW]	34	8.6	3.7	2.2	1.4	1.0
decay power into beam pipe [W/m]		520	140	58	32	21
interaction point parameters:						
rms spot size, $\sigma_{x,y}$ [μm]	0.39/0.003	1.5	0.9	0.7	0.6	0.6
rms bunch length, σ_z [mm]	0.3	1.0	1.0	1.0	1.2	1.7
$\beta^*_{x,y}$ [mm]	15/0.4	1.0	1.0	1.0	1.2	1.7
rms ang. divergence, σ_θ [mrad]		1.5	0.90	0.70	0.53	0.37
beam-beam tune disruption, $\Delta\nu$		0.013	0.026	0.040	0.065	0.100
pinch enhancement factor, H_B		1.000	1.000	1.004	1.04	1.13
beamstr. frac. E loss/collision [10^{-8}]		0.008	0.09	0.4	1	2
neutrino radiation parameters:						
collider reference depth, D[m]		200	320	400	450	500
ν beam distance to surface [km]		51	64	71	76	80
ν beam radius at surface [m]		6.7	4.2	3.1	2.5	2.1
max. dose: in-plane ave [10^{-3} mSv/yr]		0.9	0.9	0.9	0.9	0.9
str. sec. len. for 0.01 mSv/yr max. [m]		1.3	1.1	1.0	0.9	0.8

A mu-TESLA Looks Feasible So Far

✓ Growth in beam energy spread from beam loading & wake fields (see plot)

most serious issue?

c.f. 2×10^{10} for TESLA-500 ($f=1.3$ GHz)

4×10^{10} for SLC ($f=3.0$ GHz)

may limit N^{μ} to $\sim 2\times10^{11} - 1\times10^{12}$

✓ Transverse tolerances/emittance growth

$$\frac{\Delta\epsilon}{\epsilon} \sim \frac{N^2}{\epsilon} \qquad \left(\frac{N_\mu}{N_e}\right)^2 \sim 10^{4\div5}, \quad \frac{\epsilon_\mu}{\epsilon_{e,y}} \sim 10^5$$

$\Rightarrow$ same or easier

✓ Multi-bunch effects negligible because of large bunch spacing

✓ HOM Power ~ 1 W/m $\Rightarrow$ comparable to "normal" cavity heating even if not extracted

✓ Decay power into SC cavities

$P^{decay}/\text{meter} \sim 1$ W/m, $\lesssim$ 2K heat load for normal TESLA-800 operation

⋮

Particle ~~Bunch~~ $\frac{\Delta E}{E}$ vs. Δz in bunch due to wakefields & rf wave in rf cavities

1997 TESLA CDR (N = 2 x 10^10)

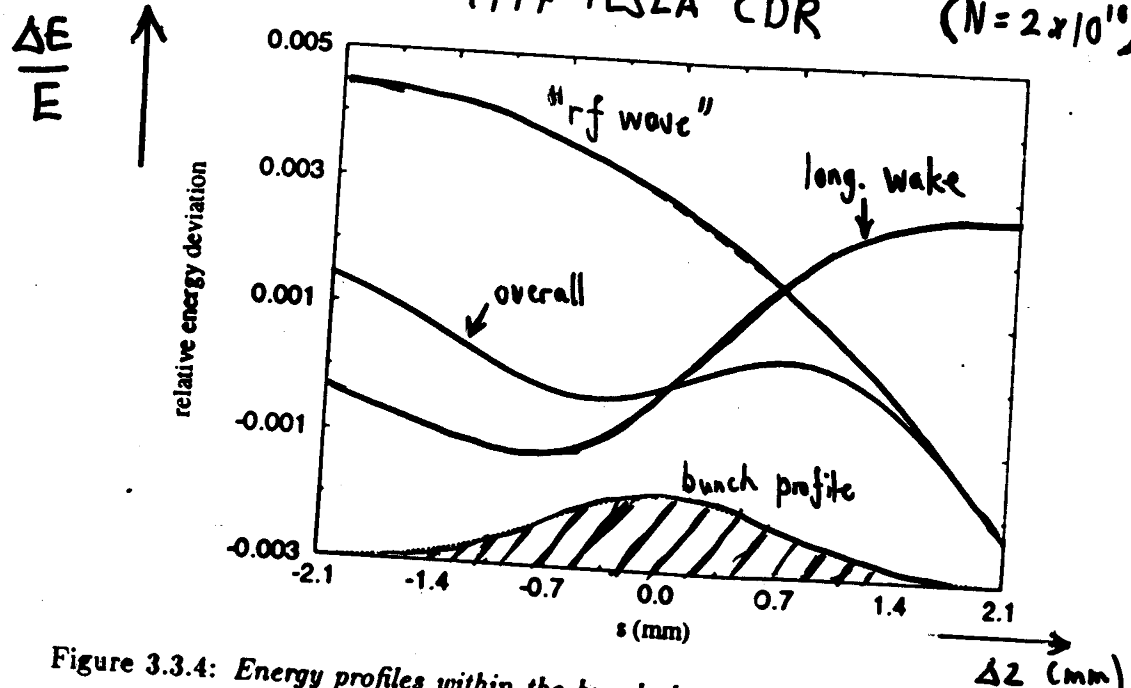


Figure 3.3.4: *Energy profiles within the bunch due to longitudinal wake (thin line), RF wave (dashed line) and both effects (thick line). The dotted line denotes the Gaussian bunch profile.*

emittance growth. For example, for a correlated energy spread, the emittance growth can be written as

$$\frac{\Delta\varepsilon}{\varepsilon} \propto \frac{\delta_c^2}{\varepsilon}\frac{1}{\beta_o^2}\frac{1}{1-\alpha}\left[\left(\frac{\gamma_f}{\gamma_i}\right)^{2-2\alpha} - 1\right] y^2$$

where δ_c is the relative rms correlated energy spread, y is the rms offset of the BPMs (including quadrupole offset and BPM offset relative to the quadrupole center). Contrary to the previous dilution driven by the cavity misalignments, the dispersive emittance dilution is lower for a less focussed beam (β_o and α large). An optimal focusing lattice, in which the dispersive effects and the wakefield effects are balanced, can then be found. Fig. 3.3.7 shows for example the vertical emittance growth, due to simultaneous chromatic and wakefields effects, driven by random quadrupole and cavity alignment errors, with different scalings of the beta function with energy. The rms quadrupole, BPM and cavity offsets are $\sigma_q = 100\ \mu m$, $\sigma_{bpm} = 100\ \mu m$ and $\sigma_c = 500\ \mu m$, respectively. We conclude that a small beta scaling, $\alpha = 0$ to 0.2, provides the smallest emittance dilutions. The mean emittance growth, computed with the chosen TESLA 500 lattice, the same misalignments and the simple "one-to-one" correction, is 12%. To alleviate the dispersive dilution, more elaborated correction algorithms have been proposed. All these methods refer to beam based alignment (correction) techniques, because the magnet misalignments (corrector settings) are deduced from BPM measurements with different beam trajectories. For example, the "shunt" technique consists in moving each quadrupole ...

Conclusions

- clear acceleration strategy for HEMC's, using rf power matched to beam

- mu-TESLA provides the missing piece of the puzzle for a TeV-scale superconducting e^+e^- linear collider: a plausible upgrade path to several TeV

  $\Rightarrow$ an idea whose time is probably coming